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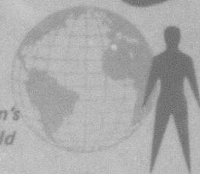
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TECHNICAL REPORT NO. 81-11

THE INVESTIGATION OF THE COMBINED USE OF MICROBAROMETRIC AND SEISMIC DATA TO DETECT AND IDENTIFY INFRASONIC SIGNALS

Semi-Annual Report #1

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There is a need to acquire an infrasonics monitoring capability to supplement existing atmospheric nuclear test surveillance systems. A research program to investigate the combined use of a three-component seismograph and a microbarograph to supply the desired monitoring capability is currently underway. A temporary observatory consisting of a five-element microbarograph array and a three-component, long-period seismograph system has been established near McKinney, Texas, to acquire the experimental data necessary to perform the investigation. Preliminary analysis of the data indicates that the

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→infrasonic signal-to-noise ratio will be greater at the output of a vertical
seismograph than at the output of a microbarograph in a frequency range
extending roughly from 0.005 Hz to 0.05 Hz during intervals of atmospheric
turbulence. Further research activities will include documentation of the
observed infrasonic SNR enhancement as a function of frequency and atmospheric
turbulence intensity; a renewed investigation into the relationship between
the yield of atmospheric nuclear explosions and the spectrum of the
resultant infrasonic signal, and studies to experimentally define the
infrasonic detection threshold as a function of frequency for a system
of instrumentation consisting of a microbarograph and a three-component
seismograph system.

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THE INVESTIGATION OF THE COMBINED USE OF MICROBAROMETRIC
AND SEISMIC DATA TO DETECT AND IDENTIFY INFRASONIC SIGNALS

Semi-Annual Report #1
by
G. G. Sorrells

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30 December 1981

CONTENTS

ILLUSTRATIONS

1.0 BACKGROUND

There is a need to improve upon our current capability to detect and identify atmospheric nuclear tests. In particular, it appears that circumstances can arise where considerable uncertainty may surround the origin and source location of anomalous signals detected by the existing atmospheric surveillance systems. It is generally agreed that the uncertainty could be significantly reduced with supplemental information provided by an infrasonic monitoring system. The purpose of this research program is to investigate a new method of acquiring the desired infrasonic information.

Atmospheric nuclear explosions produce pressure pulses which are potentially detectable at long ranges from the source. The principal energy of these pulses has been found to lie in the 0.001 - 1 Hz bandwidths. In the past, the capability to detect the infrasonic signals from atmospheric nuclear tests was vested in a network of microbarograph arrays. These arrays, which now have been largely abandoned, consisted of four or more sensors which had the intrinsic sensitivity to resolve atmospheric pressure changes as small as a few hundredths of a microbar in the bandwidth of interest for nuclear test monitoring. Unfortunately, this sensitivity could rarely be used to practical advantage to detect infrasonic signals because of the relatively large atmospheric pressure fluctuations intermittently created by the local winds. In order to combat the wind noise problem, a "pipe array" (cf. Daniels, 1959) was attached to the inlet of the microbarograph. This device is a passive wavelength filter which consists of a hollow pipe, less than 3 cm in diameter, with maximum linear dimensions on the order of several hundred meters or more, and pressure inlet ports placed at 2-4 meter intervals. Given the assumption that the wind noise is uncorrelated between inlet ports while the infrasonic signal remains correlated, it is then possible to obtain an improvement in infrasonic SNR approaching $\sqrt{N}$ where N is the number of inlets. Experiments demonstrated that while such improvements were indeed possible at relatively high frequencies (say greater than .2 - .3 Hz), the state of organization of the wind-generated noise generally precluded achievement of significant infrasonic SNR improvement at lower frequencies (MacDonald et. al., 1971). Thus, the "pipe array" is of limited value if one is interested in enhancing infrasonic SNR's over the entire frequency range of interest. Another approach which was under serious consideration in the early 1970's was to increase the number of microbarographs in the arrays by at least a factor of 3 and to rely on multichannel processing techniques to improve the infrasonic SNR (cf. Teledyne Geotech, 1971). While implementation of this approach is certainly well within the current state of the art, the probable cost of developing and operating an advanced infrasonic network leads to the consideration of alternative methods.

During the early 1970's, the AFOSR sponsored basic studies of the relationship between local atmospheric pressure changes and low-frequency seismic noise (Sorrells, 1971; Sorrells and Goforth, 1973; Sorrells and Douze 1974; Savino et al, 1972; Savino and Rynn, 1972). An important result of these investigations was the prediction and experimental confirmation that the quasi-static earth movements triggered by the passage of infrasonic waves could be detected at the outputs of a sensitive long-period seismograph system. Equally important was the prediction and observation that the earth

acts as a passive wavelength filter with respect to the atmospheric pressure
fields, selectively attenuating the shorter wavelength components to a
greater degree than the longer wavelength components. The properties of
this filter are controlled by the local distribution of elastic constants
and the depth of observation and are virtually independent of the state of
organization of the input field. Since, for a given frequency, the convec-
tive wavelength of wind-generated pressure noise may be an order of magni-
tude shorter than that of an infrasonic signal, relatively large SNR gains
are theoretically possible regardless of the state of organization of the
signal and noise field. This point is illustrated by the results shown in
figure 1. This is the theoretical infrasonic SNR gain, predicted for obser-
vations made at a depth of 100 meters in a homogenous, isotropic, perfectly
elastic half space with equivalent Lamé constants. The results shown are
appropriate for a vertical seismograph and assume that the propagation speed
of the signal is 330 m/sec while the convection velocity of the wind-
generated noise is 10 m/sec. Observe that the predicted SNR gain is greater
than 30 dB throughout the entire frequency range of interest. Conceptually
then, the earth-seismograph system may be thought of as a functional equiva-
lent to the pipe array-microbarograph system with the added advantage that
the response of the former system is virtually independent of the state of
organization of the signal and noise fields. Thus, a high-quality, long-
period seismograph system, coupled with a single microbarograph to aid in the
discrimination between seismic and atmospherically induced earth movements,
could conceivably provide the basic elements of a new infrasonic monitoring
network. The practical implications of this observation are worth noting.
Instead of developing and deploying a new generation of microbarograph
arrays, it may be possible to acquire a similar capability by adding micro-
barographs to the instrumentation already in place at selected sites in an
existing seismic network. The cost of acquiring an infrasonic monitoring
capability in this manner will be substantially lower than the deployment and
operation of an independent network of microbarograph arrays. The basic
objective of the research program currently underway is to provide the tech-
nical basis for evaluating seismograph-microbarograph options.

The basic structure of the research program may be deduced from the statement
of work shown in figure 2. The purpose of this report is to summarize
progress made during the first six months of the program.

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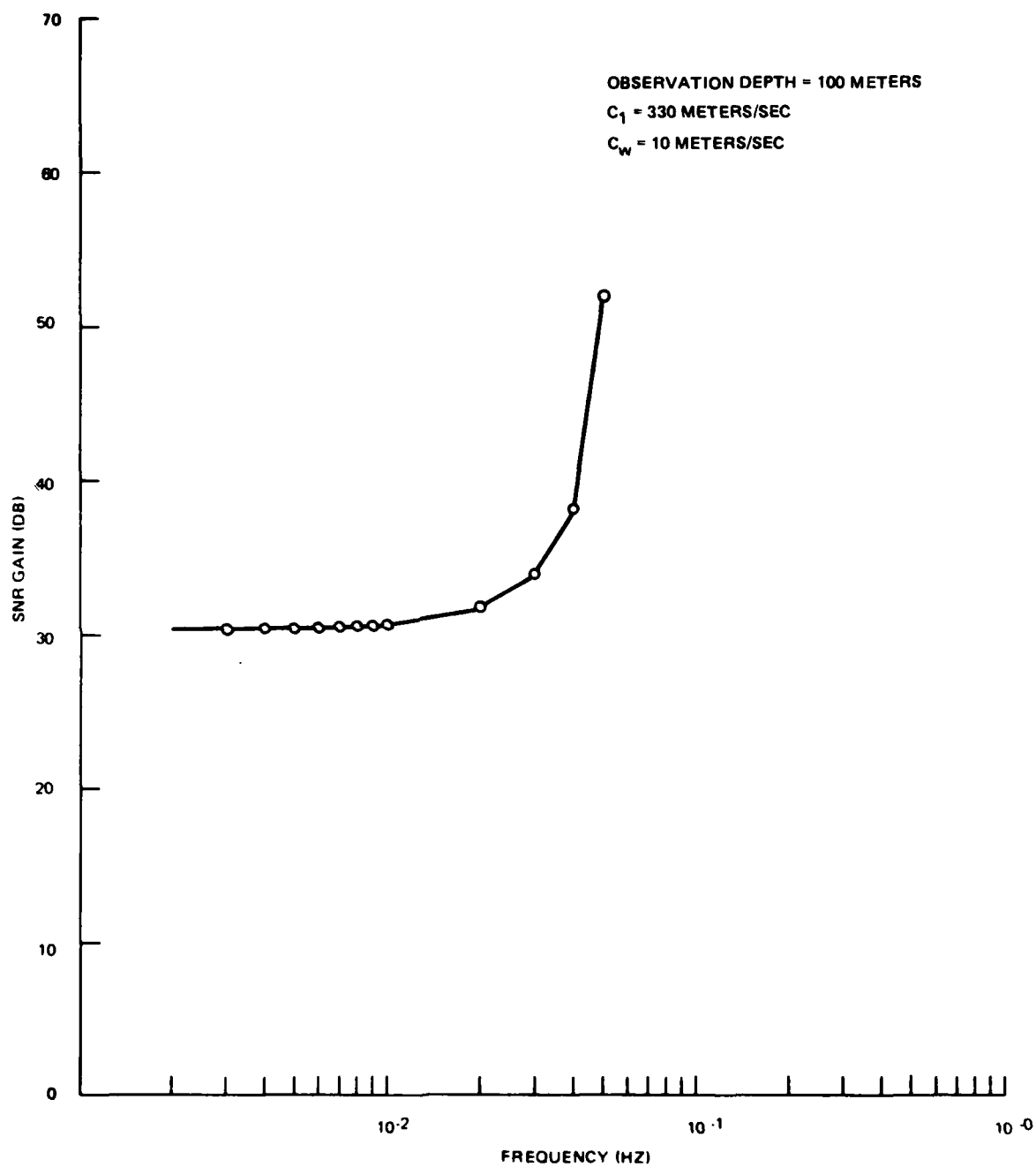
FIGURE 1. THEORETICAL GAIN IN THE INFRASONIC SIGNAL TO WIND NOISE RATIO ACHIEVED THROUGH THE USE OF A BURIED VERTICAL SEISMOGRAPH AS COMPARED TO A MICROBAROGRAPH

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Task 1. Acquire a combined microbarometric and seismic data base pertaining to infrasonic signals, subsonic noise, and seismic background noise.

Task 2. Utilize the acquired data base to experimentally assess the current capability to detect and identify infrasonic signals with combinations of the outputs of a microbarograph and a three-component inertial seismograph system.

Task 3. Investigate the feasibility of acquiring multi-component earth strain data in addition to microbarometric and inertial seismic data to assist in the detection and identification of infrasonic signal. Also investigate modifications to existing sensor systems and data processing scheme which would contribute to the detection and identification of both infrasonic as well as seismic signals.

FIGURE 2. SUMMARY STATEMENT OF WORK

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2.0 DATA ACQUISITION

The primary objectives of the first phase of the research program was to establish a temporary observatory for the simultaneous acquisition of data pertaining to earth movements and atmospheric pressure oscillations. This objective has been accomplished, and data are now being routinely recorded from a five-element microbarograph array and a three-component KS-36000 long-period seismograph system located at a depth of 150 meters at a site near McKinney, Texas. The current configuration of the microbarograph array and its location with respect to the seismograph system is shown in figure 3.

The microbarographs are of the M-4 generation and were loaned to the program by S.M.U. A 50-foot length of garden hose with 0.75 inch inside diameter is attached to the inlet port of each microbarograph. Hypodermic needles are inserted at intervals of approximately 1 meter to provide some suppression of very short wavelength atmospheric turbulence. An anemometer is also installed near the borehole containing the seismograph system to provide continuous information on the local surface wind speeds.

The seismograph is a KS-36000 three-component system and is located at 33°14'56"N latitude, 96°39'07"W longitude at a depth of 152 meters. Data from all sensing units are transmitted via cable to a central data collection facility where they are conditioned, then recorded on 35mm film for monitoring purposes. In addition, the data are sampled at 0.5 second intervals and stored on digital magnetic tape for future data processing and analysis. A block diagram of the data acquisition system is shown in figure 4. The sensor system responses are shown in figure 5.

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MCB # 5
(N 8½° W)

MAG N
8½° E

MCB # 2
(N 2½° E)
11.8m

MCB # 4
(N 59½° W)

134.7 m

727.3 m

131 m

MCB # 3
(N 58½°E)
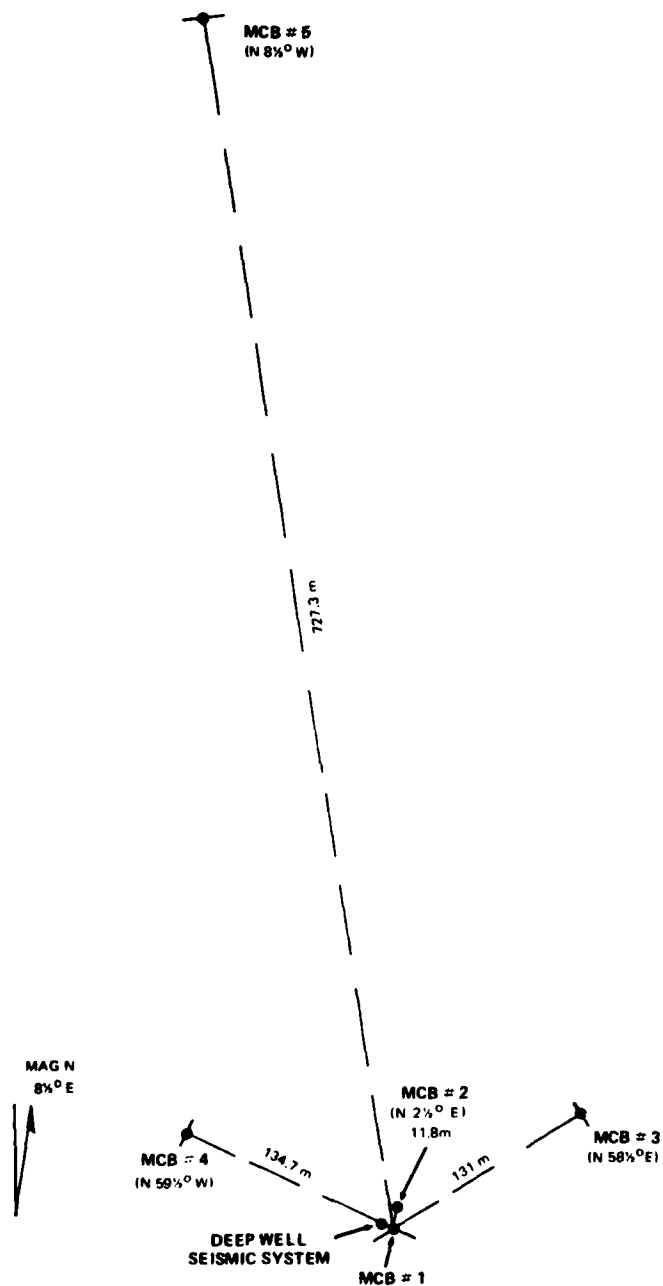
DEEP WELL
SEISMIC SYSTEM

MCB # 1

FIGURE 3. FIELD CONFIGURATION OF THE MICROBAROGRAPH ARRAY AND THE
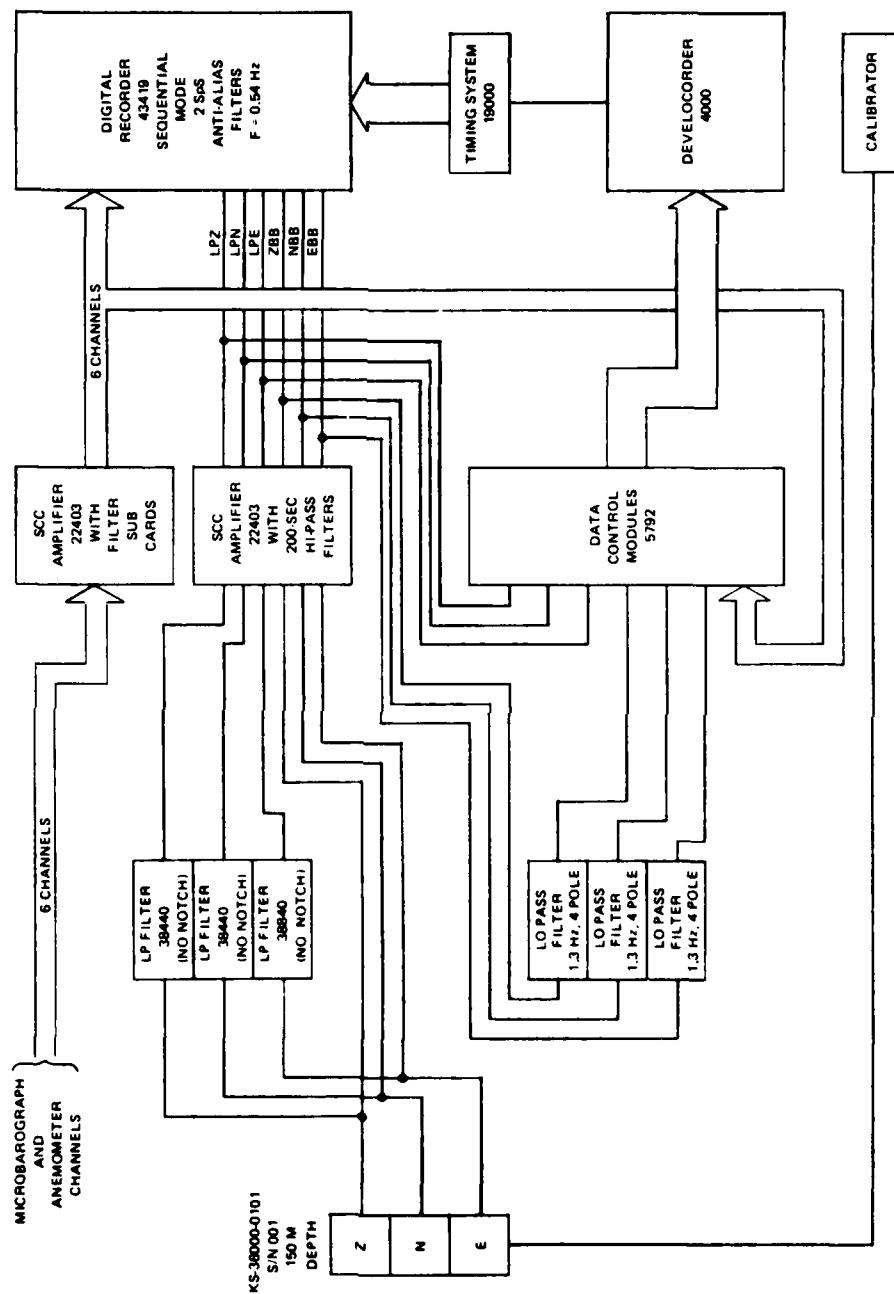DEEP WELL SEISMIC INSTALLATION

G 12345

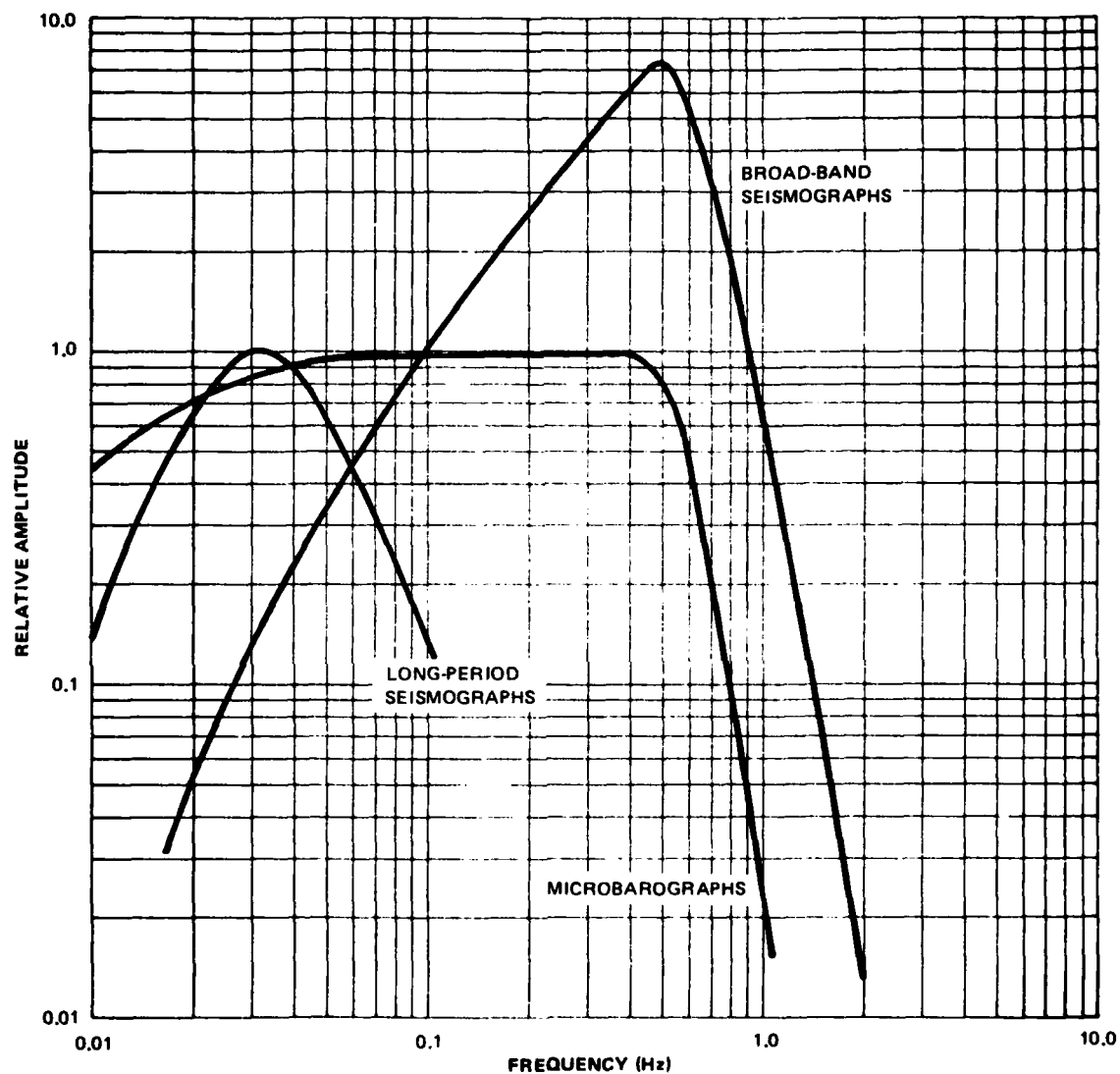TR 81-11

FIGURE 4. BLOCK DIAGRAM OF SEISMIC AND RECORDING SUBSYSTEMS

FIGURE 5. RELATIVE RESPONSES OF SEISMOGRAPH CHANNELS TO DISPLACEMENT AND
MICROBAROGRAPH CHANNELS TO PRESSURE

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3.0 DATA ANALYSIS

3.1 PRESSURE-DISPLACEMENT TRANSFER FUNCTIONS

The passage of an infrasonic wave creates quasi-static earth movements which
may be detected at the output of a seismograph system. The amplitude of
these earth movements may be related to the amplitude of the infrasonic wave
through a transfer function whose form is dependent upon the local distribu-
tion of elastic constants, the speed of the infrasonic wave and the depth of
observation (Sorrells, 1971). By approximating the earth structure at the
McKinney observatory as a layered elastic solid, theoretical transfer func-
tions may be calculated using techniques described by Sorrells and Goforth,
1973. Vertical and horizontal transfer functions appropriate for an obser-
vational depth of 150 meters at McKinney, Texas, are shown in figure 6. The
apparent horizontal displacement transfer function is the sum of the true
horizontal displacement and the apparent horizontal displacements caused by
earth tilts. It is important to note that for a pressure wave propagating at
infrasonic speeds, the vertical displacements will generally be greater than
the apparent horizontal displacements at frequencies higher than about 0.006
Hz. As shown in figure 7, this crossover point shifts rapidly to higher fre-
quencies as the propagation speed of the pressure disturbance decreases.
Now, generally speaking, the propagation speed of wind-related turbulence is
approximately equal to the mean wind speed which rarely exceeds 10 m/sec for
any sustained length of time. The comparisons of vertical and horizontal
earth movements provide the basis for a rapid means of roughly classifying
pressure-related earth movements into potential signal and noise categories;
i.e., if the observed horizontal component of earth movement is greater than
the observed vertical component and its frequency is greater than 0.006 Hz,
then, the disturbances can be safely classified as noise. If these criteria
are not satisfied, then the disturbance has a high probability of being
infrasonic in nature. This technique is now being implemented to select data
records for further processing and analysis.

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MCKINNEY EARTH MODEL (17 LAYER)

THICKNESS METERS/SEC	P VELOCITY KM/SEC	S VELOCITY KM/SEC	DENSITY GM/CM^3	YOUNG MODULUS	POISSON RATIO
60.0	1.130	0.340	1.900	0.637	0.45023
25.0	1.333	0.401	2.000	0.933	0.45026
25.0	2.100	0.700	2.100	2.968	0.43750
60.0	2.800	1.100	2.200	7.500	0.40875
150.0	2.500	0.830	2.200	5.403	0.41970
150.0	3.000	1.220	2.200	9.175	0.40093
150.0	3.400	1.630	2.200	15.791	0.36079
150.0	3.000	1.220	2.400	10.009	0.40093
450.0	3.600	1.730	2.400	19.392	0.34986
600.0	3.800	1.830	2.400	21.686	0.34903
150.0	4.300	2.300	2.500	34.375	0.29862
450.0	4.500	2.400	2.500	37.476	0.30124
150.0	4.000	2.200	2.600	32.294	0.28315
150.0	4.800	2.600	2.600	45.430	0.29238
150.0	4.300	2.400	2.600	38.152	0.27376
300.0	5.600	3.100	2.600	63.918	0.27908
0.0	6.200	3.400	2.680	79.619	0.28497

CONVECTION VELOCITY = 315 METERS/SEC

VERTICAL DISPLACEMENT

DEPTH = 150 METERS

HORIZONTAL DISPLACEMENT

APPARENT HORIZONTAL DISPLACEMENT

mμ/μbar

FREQUENCY

FIGURE 6. RESPONSE OF AN ELASTIC LAYERED HALFSPACE TO ATMOSPHERIC LOADING AT INFRASONIC VELOCITY

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MCKINNEY EARTH MODEL (17 LAYER)

THICKNESS METERS/SEC	P VELOCITY KM/SEC	S VELOCITY KM/SEC	DENSITY GM/CM³	YOUNG MODULUS	POISSON RATIO
50.0	1.130	0.340	1.900	0.537	0.45023
25.0	1.333	0.401	2.000	0.933	0.48025
25.0	2.100	0.700	2.100	2.968	0.43750
50.0	2.800	1.100	2.200	7.500	0.40975
150.0	2.500	0.930	2.200	5.403	0.41970
150.0	3.000	1.220	2.200	9.175	0.40093
150.0	3.400	1.630	2.200	15.791	0.35079
150.0	3.000	1.220	2.400	10.009	0.40093
450.0	3.600	1.730	2.400	18.392	0.34986
600.0	3.800	1.830	2.400	21.585	0.34903
150.0	4.300	2.300	2.500	34.375	0.29962
450.0	4.500	2.400	2.500	37.476	0.30124
150.0	4.000	2.200	2.600	32.294	0.28315
150.0	4.800	2.600	2.600	45.430	0.29238
150.0	4.300	2.400	2.800	38.152	0.27376
300.0	5.800	3.100	2.800	63.918	0.27908
0.0	6.200	3.400	2.880	79.819	0.28407

CONVECTION VELOCITY = 30 METERS/SEC

VERTICAL DISPLACEMENT

HORIZONTAL DISPLACEMENT

APPARENT HORIZONTAL DISPLACEMENT

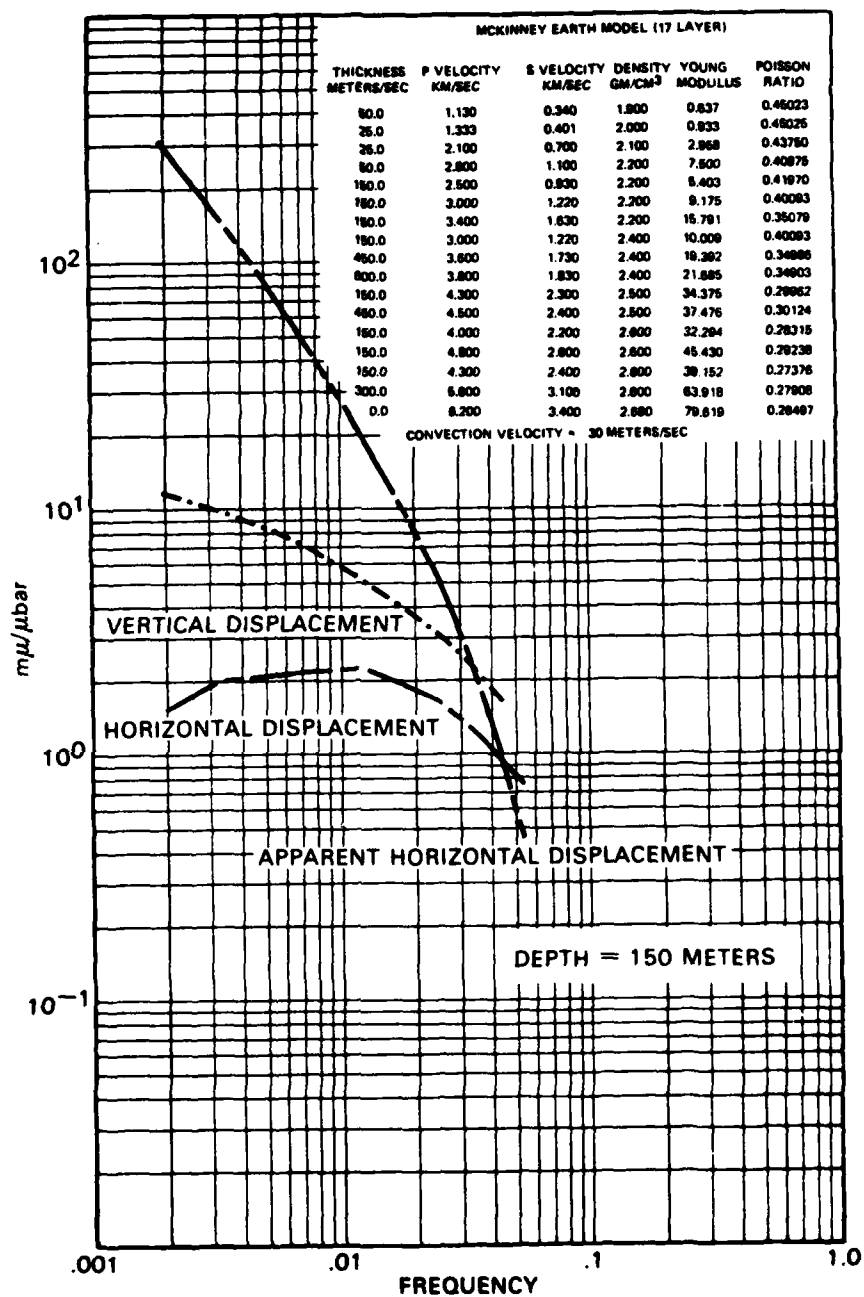DEPTH = 150 METERS

mμ/μbar

FREQUENCY

FIGURE 7. RESPONSE OF AN ELASTIC LAYERED HALFSPACE TO ATMOSPHERIC
LOADING AT SUBSONIC VELOCITY

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3.2 INFRASONIC SNR'S: PRELIMINARY RESULTS

The primary objective of the initial phase of this experiment was to establish a temporary facility for the simultaneous acquisition of digital data pertaining to local earth movements and atmospheric pressure oscillation. This objective has been achieved, and we are now in the process of experimentally evaluating the combined use of seismic and microbarometric data to detect and identify infrasonic signals. Preliminary results bearing on this subject are briefly summarized in the following paragraphs.

It was shown in an earlier section that it was theoretically possible to obtain a significant improvement in the infrasonic signal-to-wind noise ratio by transforming the detection problem into the seismic regime. In particular, it was shown that because of the passive wavelength filter properties of the earth with respect to atmospheric pressure variations, the infrasonic signal-to-wind noise ratio must always be greater at the output of a vertical seismograph than at the output of a microbarograph. In practice, however, the actual gain in SNR obtained by utilizing a vertical seismograph system will be limited by the existence of earth noise that is unrelated to atmospheric pressure variations. At the present time, there is little experimental evidence bearing upon this subject. Thus, a first objective of the data analysis is to quantitatively assess the nature of this limitation. The approach currently being followed is outlined below.

Let $m(t)$ and $u_z(t)$ denote the outputs of a microbarograph and a vertical seismograph, respectively. Then, when the wind is blowing and an infrasonic signal is present:

$$m(t) = r_m * (p_s + p_n) \tag{1}$$

Where r_m is the response of the microbarograph, p_s is the infrasonic pressure signal, p_n is the turbulent pressure noise created by the wind and (*) denotes convolution. Similarly,

$$u_z(t) = r_z *(g_{zs} * p_s + g_{zn} * p_n + n_z) \tag{2}$$

Where g_{zs} and g_{zn} are the Greens functions for the vertical component of displacement caused by infrasonic signal and wind noise, respectively. For a vertical seismograph located at a depth of 150 meters, it can be shown that

$$\langle (g_{zs} * p_n)^2 \rangle \ll \langle (n_z)^2 \rangle \tag{3}$$

so that for our purposes, equation 2 may be approximated as:

$$u_z(t) \approx r_z*(g_{zs} * p_s + n_z) \tag{4}$$

Now, the corresponding power spectra may be written as:

$$M(w) = \left| R_m \right|^2 (P_s + P_n) \tag{5}$$

$$U_z(w) \approx \left| R_z \right|^2 (\left| G_{zs} \right|^2 P_s + N_z) \tag{6}$$

Where M, U_z, P_s, P_n and N_s are the power spectral density functions associated

with m, u_z, P_s, P_n and n_z and R_m, R_z and G_{zs} are the complex terms for functions associated with r_m, r_z and g_{zs}. Rewriting equation 6 as:

$$\frac{U_z}{\left|R_z\right|^2 \left|G_{zs}\right|^2} \approx P_s + \frac{N_s}{\left|R_z\right|^2 \left|G_{zs}\right|^2}$$

$$\approx P_s + P'_n \tag{7}$$

and rewriting equation 5 as:

$$\frac{M}{\left|R_m\right|^2} = P_s + P_n, \tag{8}$$

it can be seen that the term

$$P'_n = \frac{N_s}{\left|R_z\right|^2 \left|G_{zs}\right|^2} \tag{9}$$

can be thought of as an equivalent pressure noise power spectral density estimate for the earth motion field.

Let $(SNR)_z$ and $(SNR)_m$ be the signal-to-noise ratios for the earth motion and pressure fields, then

$$(SNR)_z = \frac{P_s}{P'_n} \tag{10}$$

and

$$(SNR)_m = \frac{P_s}{P_n} \tag{11}$$

The ratio

$$I_{zm} = \frac{(SNR)_z}{(SNR)_m} \tag{12}$$

is thus a measure of the actual improvement in infrasonic signal-to-noise ratios that can be obtained through the use of a vertical seismograph. Notice that

$$I_{zm} = \frac{P_n}{P'_n} \tag{13}$$

Thus, if we confine our attention to intervals when $P_s \approx 0$ and, if we know the moduli of the transfer functions R_m, R_z and G_{sz}, we can obtain an estimate of I_{zm} from the outputs of a microbarograph and a vertical seismograph.
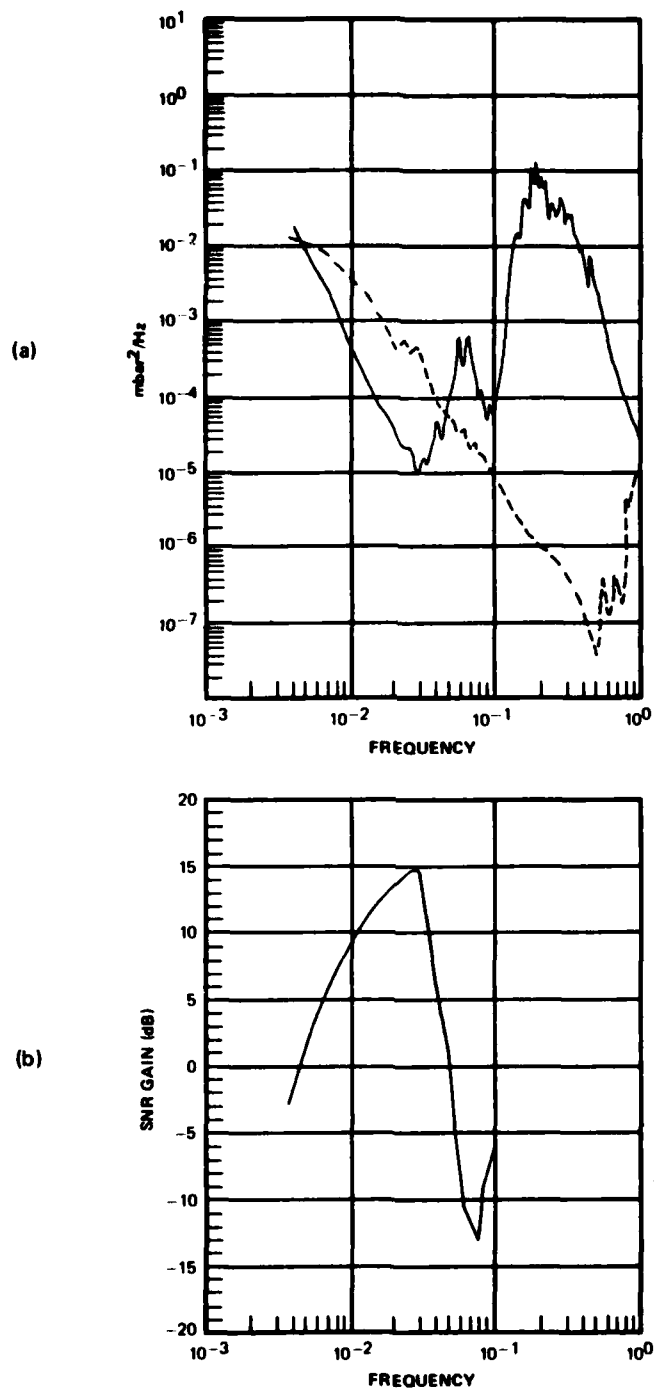
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FIGURE 8. (a) COMPARISON OF OBSERVED (SOLID LINE) AND SEISMIC EQUIVALENT (DASHED
LINE) PRESSURE NOISE SPECTRAL ESTIMATES. (b) ESTIMATED INFRASONIC SNR
ENHANCEMENT. DATA SHOWN WERE COLLECTED DURING A WINDY INTERVAL.

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We are currently making estimates of I_{zm} during various states of atmospheric turbulence given the assumption that the moduli of the transfer functions shown in figures 5 and 6 accurately depict the instrumental and earth response functions. An important preliminary result is illustrated in figures 8a and 8b. Here, we compare estimates of $P_n(f)$ and $P'_n(f)$ in a band extending from approximately 0.002 to 0.5 Hz (figure 8a) and display the corresponding estimate of $I_{zm}(f)$ (figure 8b). These results were obtained from spectral estimates of outputs of the vertical seismograph and a nearby surface microbarograph during an interval of gusty winds. The spectral estimates were made by applying the Welch method of averaging periodograms to time series consisting of 10 blocks of 1024 points. The important point illustrated by these results is that the estimated value of $P'_n(f)$ is significantly lower than the estimates of $P_n(f)$ over a frequency range extending from approximately 0.005 to 0.05 Hz. This means, in effect, that within this frequency band, the infrasonic SNR will be greater at the output of a vertical seismograph than at the output of a microbarograph during this interval. The estimate of $I_{zm}(f)$, which is shown in figure 8b, indicates that the increase in infrasonic SNR's can be as much as 15 dB in a narrow frequency band near 0.03 Hz. These results are encouraging in that they are qualitatively consistent with earlier observations made at Grand Saline, Texas, (Sorrells et al, 1971) which indicated that over a similar frequency range, the infrasonic SNR's for a presumed atmospheric nuclear explosion were higher at the output of a vertical seismograph located at a depth of approximately 180 meters than at the output of a microbarograph located at the surface.

Similar calculations have been made for data collected during calm intervals. These results are shown in figures 9a and 9b. Observe that, under these circumstances, $P_n(f)$ is less than $P'_n(f)$ throughout the entire bandwidth of interest. These results simply serve to illustrate the obvious point that in the absence of wind-generated atmospheric pressure changes, a microbarograph will be superior to a vertical seismograph for the detection of infrasonic waves.
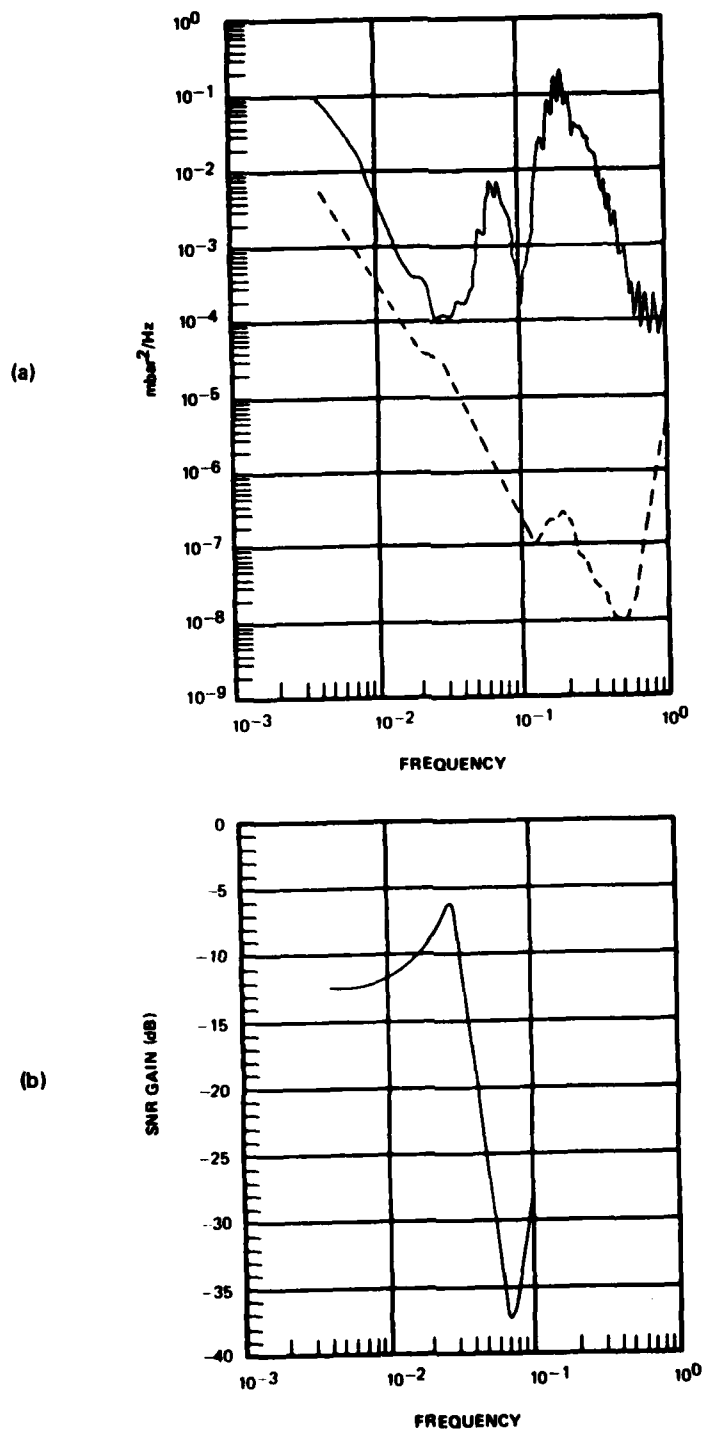
-15-

FIGURE 9. (a) COMPARISON OF OBSERVED (SOLID LINE) AND SEISMIC EQUIVALENT (DASHED
LINE) PRESSURE NOISE SPECTRAL ESTIMATES. (b) ESTIMATED INFRASONIC SNR
ENHANCEMENT. DATA SHOWN WERE COLLECTED DURING A CALM INTERVAL.

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4.0 FUTURE RESEARCH DIRECTIONS

The preliminary results presented in the previous section increase our con-
fidence that, during intervals of atmospheric turbulence, the infrasonic SNR
will be greater at the output of a vertical seismograph than at the output of
a microbarograph over a significant fraction of the frequency range of
interest for atmospheric nuclear test detection. While these results show
promise, more work needs to be done not only to document the gain in the
infrasonic SNR both as a function of frequency and the intensity of
atmospheric turbulence, but also to refine our estimates. In particular,
experimental confirmation of predicted pressure-displacement transfer func-
tion is needed since it plays a significant role in estimation of the SNR
gain.

It is also important, for the purposes of this program, to renew investiga-
tions into the relationship between the yield of an atmospheric nuclear
explosion and the spectrum of the infrasonic signal which it generates.
While it is generally recognized that the infrasonic spectrum shifts toward
higher frequencies as the yield decreases, the precise nature of the rela-
tionship is poorly known, particularly in the kiloton yield range. A
knowledge of this relationship is important in that it would allow us to
translate the observed frequency limits currently being determined to a yield
range. Be knowing the yield range over which enhanced infrasonic SNR's are
possible, the technical feasibility of developing new technology to extend
the currently observed frequency range can be realistically assessed.

Finally, the program should provide a reliable estimate of the infrasonic
signal detection threshold for a combination of sensors consisting of a
three-component seismograph and a microbarograph. It is probable that this
threshold can be determined directly from the experimental data base for fre-
quencies lower than about 0.02 Hz utilizing naturally occurring infrasonic
signals. At higher frequencies, an indirect method of estimation may be
needed.

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